A MODEL OF GLOBAL CLIMATE AND ECOLOGY

William R. Graham
Michael Warshaw

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I. INTRODUCTION

Considerable progress has been made in recent years in understanding the ecology and the effects of man's activities upon regions the size of lakes, estuaries, forests, and grasslands. As man's intrusions into these ecosystems have increased in recent decades, urgent and acute problems have arisen which demand the immediate application and extension of local ecosystem research.

There is, in addition, a problem on a larger scale, whose full extent and seriousness is only beginning to be appreciated (President's Science Advisory Committee, 1965; MacDonald, 1969; Fletcher, 1969). This is the problem of the *long term, persistent effects* of man's activities when viewed on a global scale. Will man, carrying his proliferation of works and bodies into the future, seriously (and possibly irreversibly) affect the global climate, his own food supply, and even the biological balance of the planet?

This paper will discuss the feasibility of answering, in a quantitative way, that question. (The stress on *quantitative* cannot be overemphasized in view of the qualitative emphasis given by the popular press to the horrors that await man if he continues to mistreat the planetary life support system.)

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The continual addition of carbon dioxide to the atmosphere provides an excellent case in point: as man increases his consumption of fossil fuel, an increasing amount of CO_2 is released into the atmosphere. What is predicted depends upon who is doing the predicting (Brown, 1956; Revelle *et al.*, 1965; Batten, 1966; Cormoner, 1967; Ehrlich, 1968). Some predicted results include increased plant growth rate, increased surface temperature, and massive flooding caused by melting ice caps. Perhaps there might be very little flooding, in the unlikely event that the effects of the increased CO_2 concentration are just compensated by the effects of an increased atmospheric load of particulates, inadvertently generated by man.

An understanding of the transport and circulation of carbon through the biosphere is essential for predicting the basic quantity needed in determining CO_2 effects: the buildup of the atmospheric concentration of CO_2. However, one-third of the CO_2 that is injected into the atmosphere each year, 3 billion metric tons, is being removed by some process which has not yet been identified. (See the Appendix for a discussion of the CO_2 injection and buildup rates.)

II. A GLOBAL MODEL

An effort is needed to integrate all the information at our disposal, much of it coming from a wide variety of sources, into a total, consistent model of the relationships between the biosphere and man's activities. Such a model is needed to predict the long-term, large-scale ecological results of man's actions. There is reason to believe that a model of this kind can be designed, if one is willing to accept some limitations, at least initially.

In particular, one must forgo predictions of small-scale, short-term phenomena, and look instead for models which incorporate large-scale phenomena and long-time averaging. The central uncertainty is

whether any such an approach would correctly predict important global effects.*

Although a definitive answer is not available, the benefits of achieving even a limited success warrant an attempt to develop models of the global aspects of the relationship between the biota and the environment.

The model suggested here is outlined graphically in the block diagram Fig. 1. The connecting arrows describe the casual relations among the parts of the system; they are not bi-directional. With this partitioning of the problem, one can more accurately assess the present limits of knowledge.

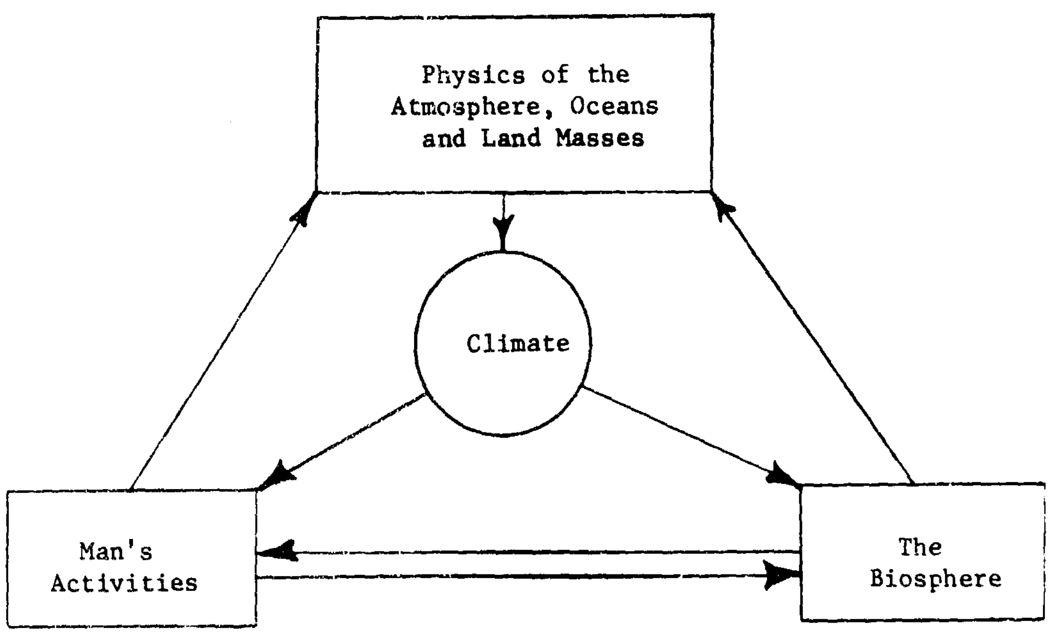

Fig. 1--Principal Features of Global Ecology Model

*An example might be the global effects of DDT. This chemical tends to migrate without wide dispersion and localizes itself in only certain species. Any attempt to average the distribution would tend to dilute the concentration, perhaps back to the sub-dangerous level. Local air pollution, localized oil spills, and detailed changes in the food chain are also beyond the model's anticipated capability.

This model is based on the assumption that climate is the central mechanism through which man's activities and the biosphere interact on a *global* scale. The climate is described by the statistical distributions over some time and space scale of variables such as temperature, humidity, precipitation, and surface wind. The choice of the scale is critical; it must not be too large to resolve climatic differences nor too small to render the problem intractable.

III. THE PHYSICS UNDERLYING THE CLIMATE

There is a distinction between the physical laws which govern the behavior of the atmosphere and sea and that collection of observables which affect the biota and are called the "climate." The climate is that part of the prevailing conditions which affect life, both directly (temperature, precipitation, etc.), and indirectly (food supply, raw materials, habitability).

The motions of the atmosphere and ocean are governed by physical laws which are expressed in the form of the equations of hydrodynamics and thermodynamics. These relationships are in principle well known from classical physics. However, for certain phenomena, such as small-scale turbulence and precipitation, the problems of applying physics to obtain useful results are formidable and only partly solved, so that the use of semi-empirical relations to approximate some effects is required. In addition, certain simplifications must be made for the sake of tractability.

The central physical problem of studying climate lies in the removal of the irrelevant detail so as to create a tractable model. A philosophically satisfying way to deal with the detail is to leave all of it in the physical model and then to perform climatic averages over the derived results. Unfortunately, this approach has two fatal flaws: first, the initial conditions are known at only a few locations, and then only occasionally, which gives very poor starting resolution. Secondly, there is not enough computing power in the world to advance a very detailed model even as fast as real time.

Therefore, a considerable amount of spatial and temporal averaging must be performed during the construction of the model, rather than during the analysis of the results. In fact, the constraint of tractability on long-term climatic calculations means that even more initial averaging must be done than in the case of elegant models of atmospheric and oceanic circulation, such as those of Smagorinsky (1965), Mintz (1965), and Bryan and Cox (1968). What becomes a central and as yet unsettled issue is whether a less complex model (e.g., MacCracken, 1968, 1969), which performs a spatial averaging *prior* to actual computation, in fact predicts a future *average* climate.

It is the choice of appropriate simplifications that has posed such a difficult problem for investigators of general circulation models. If the simplifications are too severe or unrealistic, the computation may produce predictions which, while perfectly valid from a mathematical standpoint, have little or no relationship to the future climate. If too few simplifications are made, the problem remains intractable, even with the aid of the largest computer. This is a particularly crucial subject when one desires a model which will predict the climate for decades into the future, but need attain only moderate fidelity.

Pre-averaged models have been constructed. They achieve computing speed by sacrificing spatial information; the zonally averaged model is an example. Such a model is only now being tested by comparing it with its full three-dimensional model counterpart.

The Coupled Ocean/Atmosphere Model

There are models of the atmosphere and models of the ocean, but an effective coupling of these two systems has yet to be achieved. Progress is excellent, however, and a few more years should bring the completion of at least the first three-dimensional coupled atmosphere/ocean model. The following discussion gives the reasoning behind the requirement for such a coupling [Gates, 1968].

The conservation of momentum, energy, and matter is central to any physical theory of the circulation of a fluid, and in particular to the theory of the circulation of the atmosphere and the oceans. These systems are in direct contact over two-thirds of the earth's surface, and the coupling of the two fluids is measured by the extent to which they exchange the conserved quantities.

Momentum. Momentum is transferred from the atmosphere to the surface waters primarily through the surface wind stress. This stress is very important to the ocean transport, as it is the main driving force for the oceanic general circulation. The stress provides a boundary frictional dissipation for the atmospheric circulation, which provides, in turn, a damping force on the atmospheric motion.

Energy. Most of the solar energy which falls upon the surface of the earth is absorbed in the surface waters of the oceans. This energy and its transport (controlled in part by the atmosphere) determines the temperature of the surface waters, and ultimately, of the deep waters. At lower latitudes, the energy transported horizontally by the circulation of surface water amounts to more than one-third of the atmospheric heat transport (Emig, 1967).

Some sensible heat is conducted between the ocean and the atmosphere at the interface, but a larger amount is carried into the atmosphere by blackbody radiation from the surface. The evaporating water also carries latent heat of evaporation, which is converted to sensible heat in the atmosphere when the water condenses. The latent heat flux is a principle source of energy for driving the atmospheric circulation.

Matter. The flux of water across the atmosphere/ocean boundary is the main source of water vapor for the atmosphere. The water vapor then affects the atmospheric circulation by providing a source of heat (upon condensation), and by changing the radiation balance through the formation of clouds and the direct scattering and absorption of radiation by the water molecules. The size distribution and concentration of particulates and aerosols which are added to the atmosphere also affect the radiation balance in

that they both absorb and scatter radiation. They are added to the atmosphere by such sources as volcanos, dust storms, and urban-industrial pollution; and are removed primarily by deposition into the oceans. The local difference between evaporation and precipitation also drives the salinity gradient of the oceans and the resultant circulation necessary to maintain hydrostatic equilibrium.

The amount and type of global cloud cover is even more important than the particulate content of the atmosphere in determining the temperature of the atmosphere. Manabe and Weatherald (1967) estimate that a one percent change in cloud cover will result in surface temperature changes between .39 and .82°K, the actual value depending on the altitude of the clouds. This sensitivity to cloud cover is a source of considerable concern--indications are that better methods of estimating cloudiness must be developed.

Carbon Dioxide. A much smaller but very important flux of matter across the atmosphere/ocean interface is that of carbon dioxide. Carbon dioxide has absorption bands in the infrared which, along with those of water, control the absorption and transmission of infrared from the earth into space. It has been estimated (Manabe and Weatherald, 1967) that under the condition of fixed relative humidity and radiative convective equilibrium, but *without* horizontal circulation, doubling the amount of CO_2 in the atmosphere would change the mean surface temperature by 2.36°C.

At the present, the total amount of CO_2 in the atmosphere is being increased by more than .2 percent per year (Pales and Keeling, 1965; Brown and Keeling, 1965), and the rate is probably increasing. The CO_2 added each year is apportioned between the atmosphere, the oceans, and possibly the biota (see Appendix). The rate of production of CO_2 by fossil fuel consumption has been estimated to be about 10^{16} grams/year (Revelle and Suess, 1957). If CO_2 continues to be added to the atmosphere at the present rate of .2% per year, the amount of atmospheric CO_2 will double in 347 years. However, the rate of addition of CO_2 has been increasing exponentially since at least 1880 with a doubling time of 24 years (Bolin and Eriksson,

1959). If this exponential growth continues, the atmospheric CO_2 will double in less than 83 years. The latter figure is probably the better prediction, although the exact va e depends upon global economic development and is therefore somewhat uncertain.

The measured value of the atmospheric CO_2 indicates that only about half of the estimated CO_2 produced remains in the atmosphere, the removal of the remaining CO_2 usually being attributed to absorption by the ocean (Weyl, 1970). However, the rate at which the ocean can absorb CO_2 does not seem sufficient to absorb so large a fraction of the increasing CO_2 produced each year by the burning of fossil fuel (see Appendix).

Time Span of Climatic Calculations. Experiments with a three-dimensional model of the atmospheric circulation (Mintz, 1965) indicate that the circulation is not sensitive to the initial conditions *of the atmosphere* for more than a few months. However, the circulation of the atmosphere is sensitive to the circulation of the ocean surface water, and to the condition of the atmosphere/earth interface. The initial conditions in ocean circulation models have effects which persist on the order of nine years (Bryan and Cox, 1968), and the buildup and decay of surface ice, such as was present during the last ice age, took place over times spanning several thousand years--some of the glacial ice is still present in the Antarctic and Greenland ice caps. Even fluctuations such as the "little ice age" endured two hundred years, from the middle of the seventeenth to the middle of the nineteenth century.

In order to track through the next century effects associated with the buildup of CO_2 and other chemical components, particulates, aerosols, changes in the earth's surface albedo, and surface heating by power dissipated from man's activities, one needs an atmospheric model that will simulate one hundred years or more of climatic time.

Three-dimensional atmospheric models which treat surface coupling, water vapor, and radiation transport with sufficient accuracy are at present manifestly impractical from the standpoint of the requisite computing time. Two-dimensional, zonally averaged models

have been deployed which hold much more promise for long-term climatic predictions (e.g., Williams and Davies, 1965; Sellers, 1969; Dolzhanskiy, 1969; MacCracken, 1968, 1969), and one (MacCracken, 1968) has calculated several years of averaged climate.

In the two-dimensional model, the meridional structure necessary to represent Rossby waves and cloud-producing turbulence must be approximated in such a way that the zonal variation does not appear explicitly, and the dynamical equations are averaged in the zonal direction. The model then represents the atmosphere as a series of homogeneous zones between parallels of latitude whose properties have no variation with longitude, that is, in the zonal direction. The parameterization of the effects of the zonal dimension permits a much more careful treatment of the vertical structure of the atmosphere and of the conditions on and below the surface. Vertical, zonal, and meridional winds are still considered explicitly in the two-dimensional approximation.

Currently, the most detailed zonally averaged model contains six levels of atmospheric structure and ten levels of surface structure (MacCracken,1968), and includes parametrically the effects of large-and small-scale turbulence such as Rossby waves, partial cloud cover, and precipitation. Using the ILLIAC IV computer (one quadrant), the model will predict 100 years of climate in about 5 hours of computing time, which compares very favorably with the 500 hours that would be required by a three-dimensional model such as those of Mintz (1965) or Leith (1965).

Preliminary results from MacCracken's studies of ice-age theories indicate that zonal averaging is a viable predictive tool, and the zonal model is being pursued as means to predict the global climate.

IV. MAN'S ACTIVITIES WHICH AFFECT THE CLIMATE

In order to quantify the couplings of Man's Activities shown in Fig. 1, one must first determine the ways in which man might purposefully or inadvertently cause a direct change in the processes creating the climate, or change the biosphere in a way that would indirectly modify the climate. Since man's future activities are to some extent uncertain, one must be able to predict the climate for a range of future uses of fossil fuels, changes in the earth's albedo by surface modification, and more subtle forms of intrusion into the forces determining the planetary climate.

Several different and widely prevalent activities of man have the potential for disturbing the ecology on a global scale. The most important of these may be divided into two categories: those associated with man's nonbiological energy requirements, and those associated with man's biological energy requirements--the food supply.

Man's Nonbiological Energy Requirements. Sunlight, nuclear fuels, and fossil fuels are man's main energy sources. Fossil fuel consumption must necessarily produce carbon dioxide. Lesser amounts of other gases such as oxides of nitrogen and sulfur, along with particulates are usually produced as well. It is estimated that there is a sufficient reserve of recoverable fossil fuel (primarily coal) to produce an amount of carbon dioxide equal to five times that presently in the atmosphere (Dugas, 1968). The possible effects of increasing the atmospheric concentration of CO_2 have been discussed earlier. Possible widespread effects of the other gasses are not yet known.

Airborne particulates affect the earth's radiation balance by absorbing and scattering radiation. It has been estimated that the atmospheric particulate loading caused by human activity is about half of the average total loading and is growing. The peak loading, caused by volcanic activity, is about an order of magnitude

greater than the present average loading. Experimental data indicate that statistically perceptible decreases in the average global temperature result from these eruptions (Mitchell, 1970).

Essentially all of the energy generated on the earth is eventually transported away from the surface as heat. The present ratio of energy generated to net surface solar energy input is .0004 and growing so rapidly that it may be of significance in the coming decades (MacDonald, 1969).

Man's Biological Energy Requirements. Extensive agricultural activities affect the climate through the redistribution of water, the change in the surface albedo, and the added particulate input through the exposure of topsoil to the wind. Irrigation changes the heat capacity of topsoil by maintaining its dampness. Depending upon the structure of the subsoil, much of the irrigation water may go directly into the atmosphere. The atmospheric water input from the land is still small compared with the water input from the oceans, however.

The removal of ground cover as preparation for agricultural planting will change the albedo of the surface, which then continues to change through the growing, harvesting, and wintering cycle. These albedo changes are in phase seasonally within each polar hemisphere and out of phase between them.

The contribution to atmospheric dust loading made by agricultural denudation followed by high winds is perhaps best illustrated by the U.S. dustbowl storms of the 1930's, in which several inches of topsoil from areas of the Great Plains were carried away in the atmosphere.

V. THE EFFECT OF THE CLIMATE ON THE BIOSPHERE: BIOMETEOROLOGY

The most pervasive and least understood coupling of man's activities to the biosphere occurs through the climate. The climate affects the biosphere in several ways. The state of the earth's surface is characterized by the extent and duration of ice and snow cover, the perma-frost level, and the temperature distribution in the ground. All these properties affect the biological activity on the surface.

The near-surface temperature of the atmosphere as a function of time also has a profound effect on the range of biological activity, as do the precipitation and surface insolation. Finally, the surface humidity and winds help to control the surface biota.

The above characteristics have a direct effect upon the surface biology. Less direct but of equal importance for irrigated land is the effect of precipitation and pumping upon the water table. As a result of insufficient precipitation (or overpumping), a descending water table caused several hundred thousand acres of Arizona farmland to be taken out of production during the 1960's. The precipitation also determines the maximum amount of water that can be collected from surface runoff, which places an upper bound on the amount of water that can be obtained for irrigation without extensive pumping, recycling, or water transport systems.

As changes in the global climate occur, two strategies for food production are available. One can change either the strain of crops or the types of crops which are grown. The model should be able to determine the future conditions in which new strains would have to survive, and the climatic conditions that would dictate which types of crops could be grown for the food production of the world. From these determinations, the range of potential global food production in the future could be calculated. Collateral problems, such as the global distribution of fertilizer and fuels, would be considered as possible limiting effects upon the agricultural production.

The effects of the climate on the biosphere is certainly the area where the present capacity for accurate prediction is smallest. Current bioclimatological theory of environmental tolerance must be used (Lowry, 1969) in this portion of the model, supplemented with assumptions which are incorporated into the model as a set of parameters; sensitivity analyses will be performed and a range of alternative results derived. Those uncertainties in the coupling which cause the greatest spread in possible results will then be identified for further study.

VI. SUMMARY

Table 1 shows the specific sequence in which the model might be constructed. Summing up, the model must integrate and couple what is known in many diverse fields into a single, self-consistent, tractable problem (roughly represented in Fig. 1). Where analysis or observation fails, one would resort to a range of relationships which must then await future observations for definitization.

Table 1

LONG TERM SEQUENCE OF MODEL CONSTRUCTION

Problem	Action	Result
Describe behavior of CO_2 in ocean and atmosphere.	Do Chemical and Transport analysis.	Dynamic model of atmosphere/ocean CO_2 system.
Can man affect the CO_2 content in the atmosphere?	Estimate carbon available and consumption rates.	Estimated changes in atmospheric CO_2 content.
Does a zonally averaged model of this atmospheric circulation adequately predict the real circulation?	Compare zonally averaged model with available 3-D versions.	Verification of the zonally averaged approach.
How do changes in atmospheric CO_2 affect the climate?	Derive or modify radiation and heat balance portion of model and use with air/sea model.	Predicted climate.
How do added particulates affect the radiation transport?	Modify radiation transport model as required.	Improved radiation prediction.
What are the effects of changes of earth's surface, e.g.,albedo,dust, nuclear effects?	Particulate transport and fallout analysis.	Predicted climate.

Table 1--continued

Problem	Action	Result
Does the dynamic coupling between the ocean and atmosphere affect the predicted climate?	Determine need for oceanic coupling.	Improved climate prediction.
How does the predicted climate affect the biosphere?	Analysis to provide required coupling.	Changes in food productivity.
How does the predicted climate affect man?	Analysis to provide required coupling.	Changes in earth's habitability.
Is the model self-consistent?	Include apparently significant couplings heretofore omitted in the analysis.	Consistent model of basic processes--amenable to comparison with experiment on observations over a limited range.
How does man's energy input affect the climate?	Estimates of heating rates, input mechanisms.	Predicted climate.
How does the changed biosphere and climate affect the population growth of man and his activities?	Analysis of coupling.	Prediction of survival of man and his life support system.

Appendix

THE INTRODUCTION AND REMOVAL OF ATMOSPHERIC CO_2

The volume of all of the oceans is about 1.3×10^{21} liters. The upper 75 meters accounts for the surface water or 2% of the total ocean water. The residence time of the deep water (below 75 meters) is about 1000 years; hence a volume of $1.3 \times 10^{21}/1000 = 1.3 \times 10^{18}$ liters/year flows from the deep region through the surface region.

The volume of the surface water is about 2.4×10^{19} liters, and if it is renewed from the deep water at the rate of 1.3×10^{18} liters/year, then the surface water residence time is about 19 years.

If one assumes a 30% increase in the atmospheric CO_2 by 2000 A.D. and that all of this CO_2 is injected into the atmosphere at once (for a first approximation), the atmospheric CO_2 pressure would be increased from 300 to 400 microbars by the addition of 2×10^{16} moles of carbon.

Assume further that the atmosphere and the surface waters of the oceans come into CO_2 equilibrium instantaneously. This approximation removes the rate of solution question, and gives a lower bound to the overall CO_2 removal time.

Figure A shows the change in the total dissolved carbon under equilibrium conditions in sea water as a function of the CO_2 partial pressure. The curves were calculated from the equilibrium constants given by Li [Li *et al.*, 1969]. Besides the seawater corrections, the molecules and ions specifically considered were CO_2(and H_2CO_3), HCO_3^-, CO_3^{2-}, H_3BO_3, $H_2BO_3^-$, OH^-, H^+, and M^+, the alkalinity of the seawater, about 2.5×10^{-3} equivalents/liter. Figure A shows that increasing the CO_2 partial pressure from 300 to 400 microbars increases the total carbon concentration in the surface water from 2.26 to 2.32 millimoles/liter, a change of .06 mm/l or about 2.7%. Multiplying 6×10^{-5} moles/liter by the volume of the surface water, 2.4×10^{19} liters, gives an initial absorption by the ocean of 1.4×10^{15} moles of carbon, 7% of the total carbon added to the atmosphere. Since the

surface water is renewed with deep water every 19 years, if one assumes that the deep water is initially in equilibrium with the 300 microbar CO_2 atmosphere, an e-folding time for CO_2 removal of 19 years/.07 = 270 years results.

Estimates for the residence time of CO_2 in the atmosphere place it between 5 and 10 years; hence the surface water would be able to come into equilibrium with the atmosphere during the water's 19 year residence time.

It is possible to make a rough check on the atmospheric CO_2 removal time. It is estimated [Bolen and Eriksson, 1959] that atmospheric CO_2 has increased by at most 10% or 2.5×10^{17} grams in the last 100 years. Revelle and Suess [1957] estimate that the fossil fuel production of CO_2 is now about 10^{16} grams/year. Therefore, the atmospheric CO_2 rate equation would be

$$\frac{d\,CO_2}{dt} = 10^{16}\ \text{g/year} - \frac{2.5 \times 10^{17}\,\text{grams}}{270\ \text{years}} .$$

The change in atmospheric CO_2 in one year should then be 9×10^{15} grams, almost all of the CO_2 added.

Measurements of the increase in the lower atmospheric CO_2 concentration at Hawaii and Antarctica for 5 years indicate that the concentration is increasing by .7 parts per million per year, or 6×10^{15} grams/year [Pales and Keeling, 1965], [Brown and Keeling, 1965]. This rate of increase corresponds to a removal time of 60 years, rather than 270 years. The mechanism causing the additional CO_2 removal is not presently known.

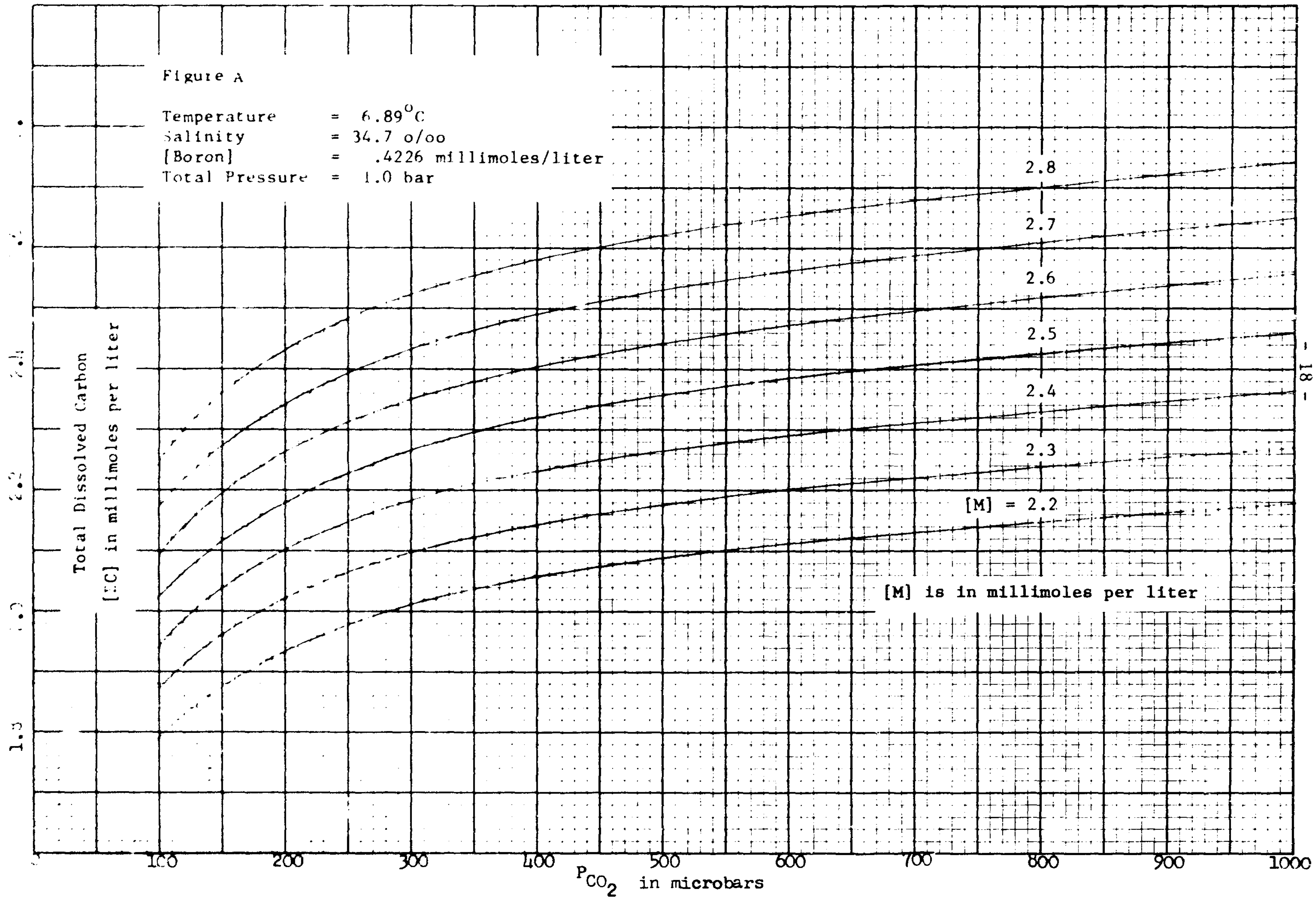
Figure A
Temperature = 6.89°C
Salinity = 34.7 o/oo
[Boron] = .4226 millimoles/liter
Total Pressure = 1.0 bar
2.8
2.7
2.6
2.5
2.4
2.3
[M] = 2.2
[M] is in millimoles per liter
Total Dissolved Carbon
[ΣC] in millimoles per liter
100
200
300
400
500
600
700
800
900
1000
P_{CO_2} in microbars

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